

# Lateral and cyclic responses of model piles in electrically treated clay

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An innovative technique to improve the capacity of piles installed in soft clayey soils using high-voltage electrokinetics was investigated in the present study. A large-scale testing facility was established to execute the treatment and perform loading tests on the model piles. Eight steel pipe piles were installed in two identical cylinders filled with simulated marine sediment. Five electrically insulated electrodes were installed close to the piles to develop a non-uniform electric field in the test cylinder. Negative DC voltages of  $-20$ ,  $-30$  and  $-10$  kV were applied in three phases for 33 days in the treatment cylinder. Lateral and cyclic lateral loading tests were performed, and the results were compared for both cylinders after each phase of treatment. The pile response was presented in terms of the experimental load–deflection curves. It was observed that the lateral capacity increased 81, 60 and 12% after the first, second and third treatment phases, respectively. The pile stiffnesses increased, and the displacements at the peak amplitude of the cyclic load decreased, due to the treatment. The improvement in the cyclic performance of the piles was evaluated in terms of the change of the soil degradation factors. The soil degradation factor increased 4.6, 14.6 and 2% after the first, second and third treatment phases, respectively.

**Keywords:** Bearing capacity; clay; electro-chemical treatment; foundations; model tests; shear strength

## Introduction

Piles have been widely used as components of structural foundations for massive structures built on weak deposits, and may be subjected to different types of loading. These structures have included nuclear power plants, multistorey buildings and offshore structures. The foundation soils in many situations were soft clays, which posed a challenge to engineers because of their low strength and the potential for large settlements of supported structures. Cost-effective foundation systems coupled with a certain degree of safety are thus needed.

It has been the aim of soil improvement to bring about a condition where the properties of the subsoil are sufficiently

Nous étudions ici une technique novatrice visant à améliorer la capacité des pilotes dans des sols argileux tendres au moyen d'une électrocinétique à haute tension. Une installation d'essai grandeur nature a été créée pour effectuer le traitement et faire les tests de chargement sur la maquette de pilotes. Huit pilotes en tube d'acier ont été installés dans deux cylindres identiques remplis de sédiments marins simulés. Cinq électrodes à isolation électrique ont été placées près des pilotes pour produire un champ électrique non uniforme dans le cylindre d'essai. Des tensions c.c. négatives de  $-20$ ,  $-30$  et  $-10$  kV ont respectivement été appliquées en trois phases pendant 33 jours dans le cylindre de traitement. Nous avons fait des essais de chargement latéral et cyclique latéral et nous avons comparé les résultats obtenus dans les deux cylindres après chaque phase de traitement. Nous avons présenté la réponse des pilotes sous forme de courbes de déflexion de charges expérimentales. Nous avons observé que la capacité latérale augmentait de 81, 60 et 12% respectivement après la première, seconde et troisième phase. Nous avons constaté que la rigidité du pilote augmentait et que les déplacements à l'amplitude de crête de la charge cyclique diminuaient à cause du traitement. Nous avons évalué l'amélioration de la performance cyclique des pilotes en nous basant sur le changement des facteurs de dégradation du sol. Le facteur de dégradation du sol augmente de 4.6, 14.6 et 2% respectivement après la première, seconde et troisième phase de traitement.

improved to provide cost-effective solutions for foundation problems and to minimize maintenance costs. Objectives of soil improvement are usually to increase shear strength and reduce long-term settlement, which otherwise could create serious problems. Improvement of clayey soils can be achieved by stabilization methods such as preloading consolidation, chemical grouting (Baker, 1982) and compaction grouting (Mitchell, 1981).

Traditional methods of soil improvement are not cost-effective for pile foundations, and in some cases are impossible to execute. Therefore, new soil improvement techniques are needed, especially in the offshore environment. Two approaches to the electrical strengthening of soft clay have been studied over the years, namely electro-osmosis and high-voltage electrokinetics.

Electro-osmosis, the first approach, involves the transport of soil pore water under the influence of a DC electric field. Soderman and Milligan (1961) used electro-osmosis to in-

crease the bearing capacity of steel H piles installed in soft-to-firm varved clay as part of the Big Pic River Bridge project. They reported that the pile capacity had increased 2.5–3 times after 4 weeks of treatment. Thirty years later, the piles were tested again and showed the same capacity (Milligan, 1995). Bozozuk and Labrecque (1969) used electro-osmosis to reduce the negative skin friction loads on 1 m diameter, 82.3 m long composite piles. These piles were installed in deep beds of compressible marine clay to support a bridge over Highway 41 at Berthierville, east of Montreal, Canada. The treatment was partially successful at the time of execution; however, subsequent measurement of pile deformation indicated that the negative skin friction loads began to build up again soon after the experiment was finished.

The second approach is high-voltage electrokinetics, which involves the application of a high-voltage electric field to the soil through electrically insulated electrodes. Improvement of the clay properties using this approach is attributed primarily to two mechanisms, namely electrophoresis and dielectrophoresis (Shang and Dunlap, 1996). The former is generated by a DC electric field, while the latter is attributed to the action of a non-uniform electric field, that is, the electric field varies as a spatial function. Pohl (1978) developed the theory of dielectrophoresis. Incullet and Lo (1988) studied the application of high-voltage dielectrophoresis to improve the properties of soft clay. Lo *et al.* (1994) used an AC voltage of 15 kV to strengthen sensitive Leda Clay in laboratory experiments. Their results showed that the clay properties improved significantly after 28 days of treatment. Shang and Dunlap (1996) investigated the effect of the application of a high-voltage DC electric field on the pull-out resistance of metallic anchor models embedded in marine sediment. They reported an increase of the pull-out resistance ranging from 18.0% after 6 days of treatment to 53.9% after 26 days of treatment. It was safe and easy to apply a high-voltage DC electric field since it eliminates displacement current induced by electric capacitance. Electrophoretic and dielectrophoretic forces are imposed on clay particles after applying a high voltage, which alters the soil structure and interparticle bonding. This leads to cementation of clay particles and consequently increases the shear strength of the clay.

The successful application of high-voltage electrokinetics in strengthening soft clayey soils has now been extended to the improvement of the capacity of piles installed in soft marine sediments. The use of high-voltage electrokinetics to improve pile capacity and enhance its performance under lateral and cyclic lateral loading conditions was explored in the present study. Laboratory tests were conducted to investigate the effect of using a high-voltage DC field to improve the engineering properties of the soil around the piles and its impact on the pile response to different types of loading. DC high voltages with different intensities were applied through insulated electrodes for a certain time period. The efficiency of the treatment technique was evaluated in terms of the change of the soil shear strength, lateral capacity of piles and the stiffness and deflection of piles under cyclic lateral loading. Abdel-Meguid *et al.* (1998) reported on the effect of the treatment on the soil properties and the axial response of the piles. The focus of the present paper is the effect of the treatment on the lateral static and cyclic response of piles.

## **Programme of experimental study**

The experimental program consisted of three phases used to study the effects of high-voltage electrokinetics on soil

properties in the vicinity of piles as well as the pile response to static lateral and cyclic loading. A high-voltage DC electric field was applied in each phase in the treatment cylinder for 33 days with the same electrode configuration and the same piles and electrode arrangement. A series of soil and pile tests was carried out, and the results were compared for both cylinders after each phase. The initial soil properties and pile capacity were measured prior to high-voltage electrokinetic treatment.

### **Experimental set-up**

The experiments were conducted in the Structural Laboratory at the University of Western Ontario. The testing facility was designed to allow for both soil treatment and pile load testing. Three series of tests were carried out on model piles installed in simulated marine clay to investigate the effects of the high-voltage electrokinetic treatment on soil and pile behaviour. A brief description of the testing facility is given here; further details can be found in Abdel-Meguid *et al.* (1998).

### **Soil chamber**

The test soil was enclosed in two identical steel cylinders. One cylinder was used to implement the high-voltage treatment (test cylinder) and the other was a control cylinder used to compensate for the effect of natural drying and ageing of the soil. Each cylinder had an internal diameter of 1.37 m and a depth of 1.52 m. Four piles were installed in each cylinder at a spacing of about nine times the pile diameter,  $B$ . The cylinders were lined with air bladders so that the soil could be pressurized. The testing area was fenced, and the cylinders and the surrounding fence were connected to the ground return. Fig. 1 shows an oblique view of the testing facility.

### **Soil preparation**

The soil used was dark-brown clay from a natural deposit recovered from London, Ontario, Canada. The grain size distribution indicated that the soil consisted of about 42% clay and 24% silt according to the MIT classification system. The organic content of the soil was 1.84%. The soil was dried, crushed and blended with sodium chloride solution at a concentration of 10 g/l to obtain a soil composition comparable to that of the offshore environment. The soil was then poured into the cylinders in ten layers to saturate the soil and to allow for self-weight consolidation. After all the soil had been poured, an air pressure of 30 kPa was applied to both cylinders for 1 week through the air bladders, the soil surface was covered with steel plates and drainage valves at the bottom of the cylinders were opened to allow for drainage. The valves were closed after 40 days of consolidation, and salty water was added to keep the clay surface submerged during the treatment and testing processes.

Soil samples were recovered from the cylinders to determine the Atterberg limits of the clay. The liquid limit was found to be 43.3%, and the plastic limit was 32.6%. Furthermore, the water content and shear strength were measured in both cylinders at different locations in three layers and found to be consistent (Abdel-Meguid *et al.*, 1998). The conductivity of the prepared clay slurry was determined from laboratory measurements, and was found to be 0.65 S/m.

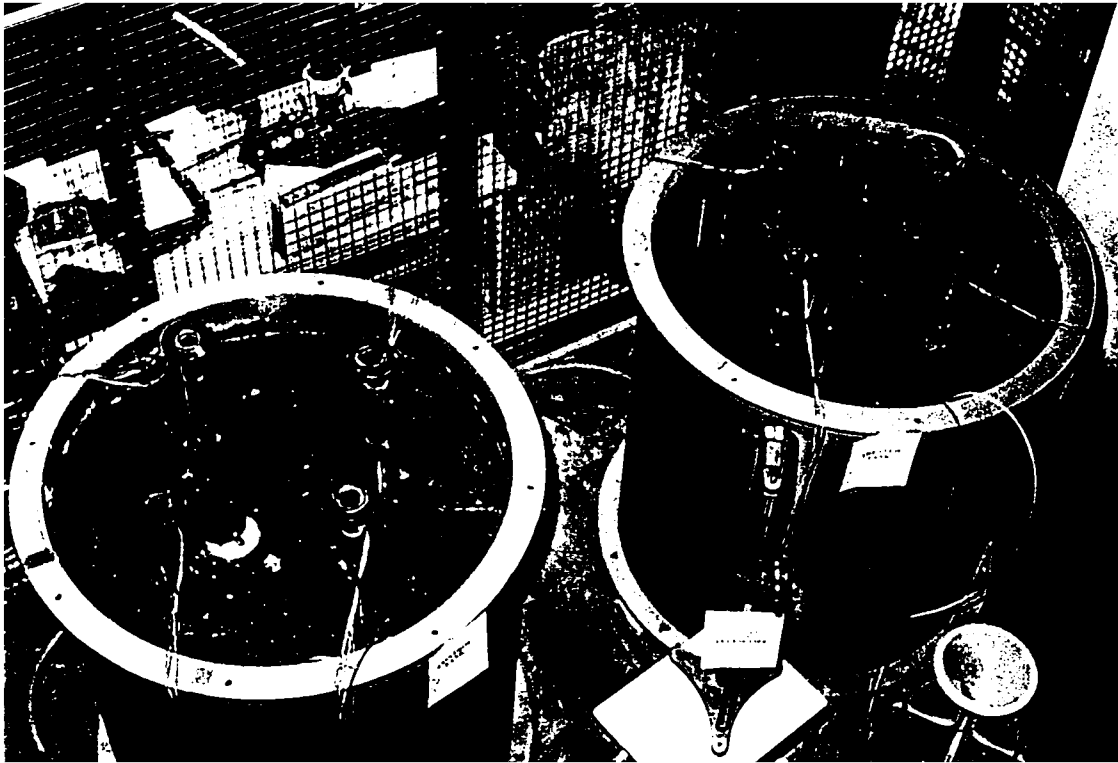


Fig. 1. Oblique view of the testing facility

### Electrical equipment

The high-voltage electric field was applied through electrically insulated electrodes made of solid copper rods 9 mm in diameter and 1.22 m in length. The electrodes were insulated using shrinkable Teflon tubing. The tops of the electrodes were fitted with brass bolts to facilitate the wiring connection between the electrodes. The embedded length of the electrode into the soil was 0.90 m. Five electrodes were installed in the test cylinder so that a central grounded electrode was located coaxially within four outer high-voltage electrodes. Each high-voltage electrode was installed 0.15 m from one pile in order to maximize the electric field around the piles. The distance between each pair of electrode and the corresponding pile was carefully chosen to prevent electrostatic discharge through the air. The high-voltage electrodes were connected to the high-voltage power supply using high-voltage cables.

Two DC power supplies with different capacities were used in the present study to investigate the effect of electric field intensities on the soil behaviour and pile responses. A power supply with an output voltage of 0–22 kV and an output current of 0–35 mA was used to apply –20 kV in the first phase of testing. The second power supply with an output voltage of 0–36 kV and an output current of 0–30 mA was used to apply –30 and –10 kV in the second and third phases of testing, respectively. Both power supplies had self-shutdown features when the current between the high-voltage and the grounded electrode exceeded a preset value. This helped in detecting any potential insulation problems of the electrodes and ensured safe operation.

### Static lateral loading set-up

The lateral loading set-up is shown schematically in Fig. 2. The lateral load was applied to the pile head at a distance of 0.33 m from the clay surface. A steel clamp was fixed

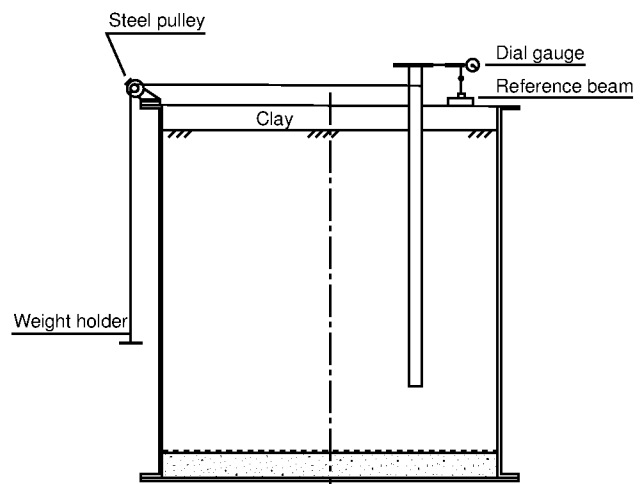


Fig. 2. Lateral loading test set-up

around the pile shaft at a specified location, and a steel wire was connected to the pile shaft at one end and held a load hanger at the other end. The steel wire passed over a pulley fixed to the rim of the cylinder using a steel bracket. The lateral load was applied by adding standard weights to the load hanger. A dial gauge attached to a fixed reference beam was used to measure the lateral displacement of the pile.

### Cyclic loading set-up

The cyclic lateral loading set-up is shown schematically in Fig. 3. Two-way cyclic lateral loading was applied to the pile at a distance of 0.33 m from the clay surface. The test set-up consisted of two pulleys aligned horizontally with the pile and fixed to the rim of the cylinder using steel brackets. The same lateral loading mechanism described above was adapted by using two steel wires to apply the loads from

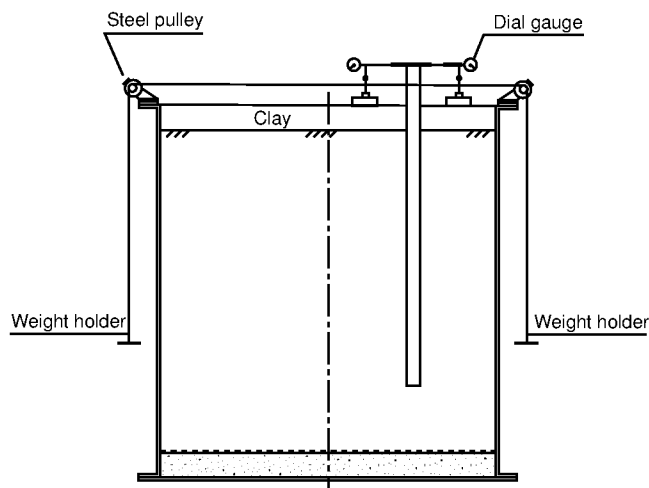


Fig. 3. Cyclic loading test set-up

both directions. The load was added incrementally in each loading direction using standard weights. The lateral displacement was measured using two dial gauges mounted horizontally at the pile flange and aligned with the loading direction at two opposite locations.

## Test results

A negative high voltage of 20, 30 and 10 kV was applied for 33 days in the treatment cylinders in the first, second and third phases, respectively, with the same electrode configuration and the same piles. The lateral and cyclic lateral tests were carried out, and the results were compared for both cylinders after each phase. The treatment effect on the undrained shear strength of the soil, lateral pile capacity and cyclic performance was investigated by comparing the performance of the piles in both cylinders in terms of the percentage of increase, which was defined as follows:

$$\% \text{ increase} = \frac{F(\text{treated}) - F(\text{control})}{F(\text{control})} \quad (1)$$

where  $F$  is the soil or pile property being considered.

## High-voltage application (phase I)

The electrical treatment in phase I was completed successfully using a  $-20$  kV DC voltage of negative polarity for a period of 33 days. The settlement of the clay surface at both cylinders was monitored during the treatment process by measuring the relative displacement between the settlement pins and a fixed object. No significant displacement occurred as a result of the treatment (Abdel-Meguid *et al.*, 1998). A series of soil and pile tests was carried out in both cylinders after treatment to evaluate its effects on the soil and pile response.

### Treatment effect on lateral pile capacity

Two piles were subjected to lateral load testing, one in each cylinder. The load was applied incrementally with a constant time interval of  $2\frac{1}{2}$  min between increments. A load increment of  $19.6$  N ( $2.0$  kg) was adopted for the tests. The loading test continued until failure was reached based on the generally accepted criteria for estimating the ultimate lateral load, that is, the lower of the load corresponding to  $6.25$  mm lateral movement and the load corresponding to the point of intersection of tangents on the load–movement curve (Prakash and Sharma, 1990).

The load–displacement relationship is shown in Fig. 4. It can be seen that both piles exhibited the same displacement until a load of  $0.08$  kN was reached. The pile in the control cylinder then started to display a weaker response than the pile in the test cylinder. The failure load was considered to be the load corresponding to the point of intersection of tangents on the load–displacement curve. The failure load for the pile in the control cylinder was found to be  $0.14$  kN. The pile in the test cylinder failed at  $0.25$  kN, indicating that an increase of about  $81\%$  was achieved using the high-voltage electrokinetic treatment.

Shear strength measurements were obtained using a shear vane test at three different points and three depths in both cylinders after the treatment. The average undrained shear strength in the test cylinder increased by  $13\%$ , and the shear strength in the control cylinder increased by  $6\%$  (due to the ageing effect), with a relative increase of only  $7\%$  (Abdel-Meguid *et al.*, 1998).

Broms (1964) defined the ultimate lateral capacity of a short rigid pile as the load inducing plastic failure of the soil along the full length of the pile. For a flexible pile, the

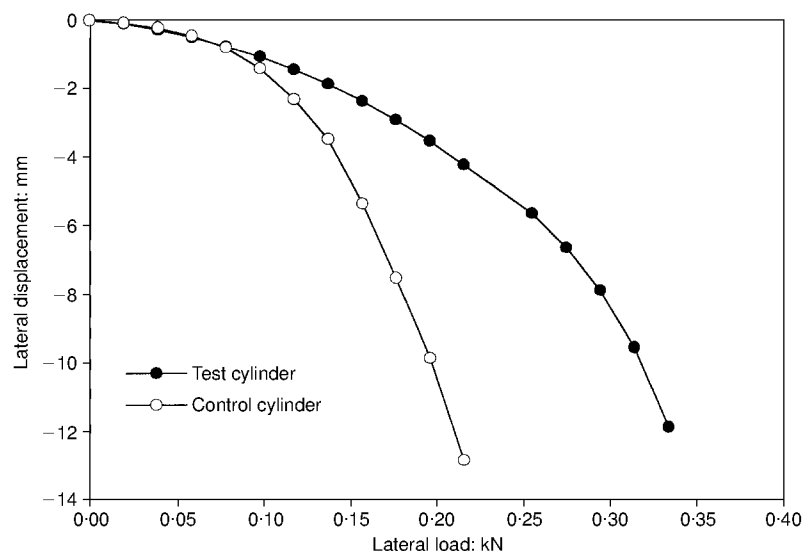


Fig. 4. Lateral load–displacement curve (first phase of treatment)

ultimate condition is reached when a plastic hinge forms at the maximum pile bending moment position (Broms, 1964; Poulos and Davis, 1980). The model piles used in this study were considered to fail as rigid piles. In this failure mode, the pile capacity depended on the undrained cohesion of the soil,  $c_u$ , and the pile diameter,  $B$ .

The ultimate static lateral resistance of cohesive soils is approximately  $2c_u B$  at the ground surface, increasing to  $8c_u B$  to  $12c_u B$  at a depth of about three pile diameters. Broms (1964) used a simplified distribution of the soil resistance to predict the ultimate lateral capacity of the pile. He assumed zero soil resistance from the ground surface to a depth of  $1.5B$  and a soil resistance equal to  $9c_u B$  below that depth. He then used the principles of structural analysis to compute the ultimate lateral load capacity.

According to Broms's model, the measured lateral load capacities suggested that the undrained shear strength of the soil had increased by 81%, not 7% as was measured using the shear vane test. This could be attributed to the fact that the shear strength measurements were taken at midpoints between the piles (i.e. 0.25 m from each pile). This indicated that the soil shear strength in the close vicinity of the pile in the test cylinder had significantly increased after applying the high voltage, resulting in the enhancement of pile lateral capacity. This observation suggested that the high-voltage electrokinetic effect was most significant within the annular zones around the electrodes installed near the piles. Therefore, the high-voltage electrokinetic technique was considered to be efficient for pile foundations, as the improvement effect can be concentrated in the local vicinity of piles by appropriate electrode arrangement.

#### Treatment effect on cyclic response of piles

The two-way lateral cyclic response test of two identical piles in the control and treated cylinders was carried out after the first phase of soil treatment. The set-up discussed earlier was adopted to perform the test. The load was applied incrementally with a constant time interval between increments of  $2\frac{1}{2}$  min. A maximum cyclic load of about 50% of the lateral pile capacity was selected to prevent the failure of the pile during the cycling process. Four lateral load increments of 0.02 kN were applied to the pile head in each direction in this test. The same sequence was followed for the loading and unloading in both directions.

The load–displacement relationship during the loading phase of the first cycle for both piles is shown in Fig. 5. It can be seen from Fig. 5 that the initial pile stiffness in the test cylinder was greater than that in the control one. The pile stiffness for the test and control cylinders was found to be 0.16 and 0.10 kN/mm, respectively, with an increase of about 54.6% after applying the high-voltage treatment. The increase in stiffness resulted from an increase of the soil modulus. Furthermore, the displacement of the pile in the test cylinder at the maximum amplitude of the load was 0.64 mm while the displacement of the pile in the control cylinder was 1.04 mm, a reduction in displacement of approximately 40%. This reduction in displacement is favourable because the design of piles, in most cases, is governed by displacement considerations.

The load–displacement relationship for the first and the 15th cycle is shown in Fig. 6. It can be seen that the pile in the control cylinder experienced larger displacements than the pile in the test cylinder after the first cycle and the difference in the displacement increased after the 15th cycle. Also, the pile stiffness, approximated by the slope of the hysteretic loop, increased in the first and 15th cycles due to the treatment.

Degradation factors, which express the ratio of the parameter after cyclic loading to the value of the parameter for a single static load application, were a convenient means of defining the effects of cyclic loading on soil parameters. The degradation factor for the soil modulus,  $D_E$ , was

$$D_E = \frac{E_c}{E_s} \quad (2)$$

where  $E_c$  is the soil modulus after cyclic loading and  $E_s$  is the soil modulus for static loading. Similarly, the degradation factor for the soil yield pressure was defined as

$$D_p = \frac{p_{yc}}{p_{ys}} \quad (3)$$

where  $p_{yc}$  is the limiting pile–soil interaction stress (yield pressure) after cyclic loading and  $p_{ys}$  is the soil yield pressure for static loading. Idriss *et al.* (1978) suggested that both  $D_E$  and  $D_p$  could be expressed as

$$D_p = D_E = N^{-t} \quad (4)$$

where  $N$  is the number of cycles and  $t$  is the degradation

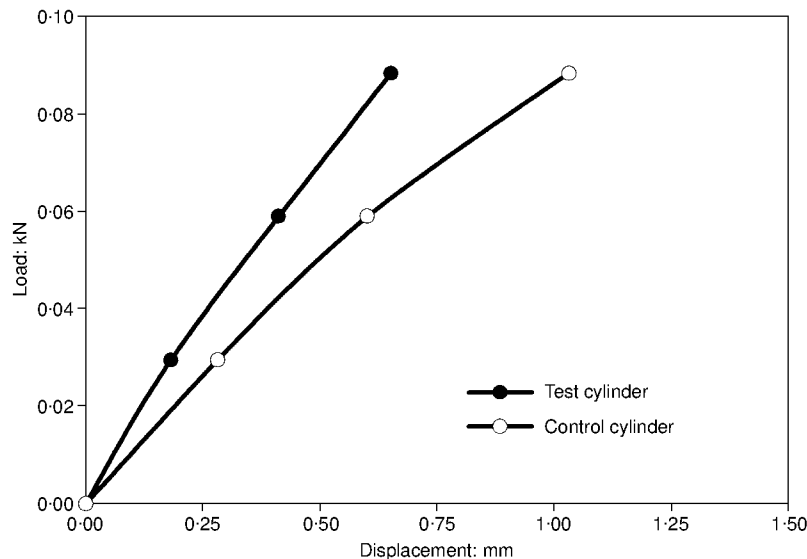


Fig. 5. Load–displacement curve during the loading phase of the first load cycle (first phase of treatment)

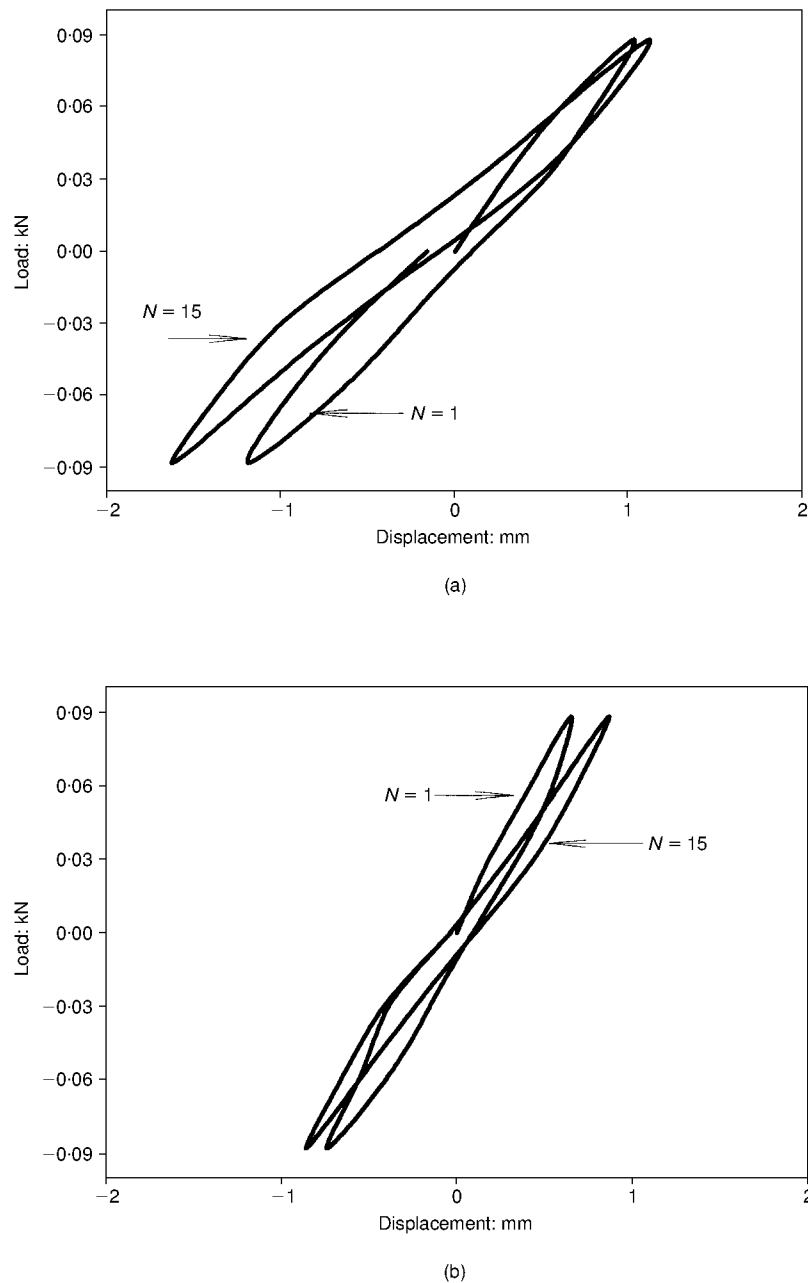


Fig. 6. Load–displacement curve for  $N = 1$  and  $N = 15$ : (a) control cylinder; (b) test cylinder (first phase of treatment)

parameter depending on the ratio of cyclic strain,  $\epsilon_c$ , to a reference cyclic strain,  $\epsilon_{cr}$ , taken as 0.01 in the present calculations. For both piles,  $\epsilon_c$  was calculated as

$$\epsilon_c \approx \frac{y_c}{6B} \quad (5)$$

where the lateral deflection  $y_c$ , corresponded to the maximum lateral load at the 15th cycle. It was found that after 15 cycles, the degradation factors  $D_p = D_E = 0.85$  and 0.81 for the piles in the test and control cylinders, respectively. This result represented a 4.6% improvement of the cyclic performance of the pile in the test cylinder.

### High-voltage application (phase II)

Lateral static and cyclic load tests were performed on two identical piles in the control and test cylinders after applying a  $-30$  kV DC voltage for 33 days. The test was performed using the set-up discussed earlier.

### Treatment effect on lateral pile capacity

The lateral load was applied incrementally to the pile until failure occurred. Load increments of 0.02 kN were applied with a constant time interval of  $2\frac{1}{2}$  min. The load–displacement relationship is shown in Fig. 7.

It can be seen from Fig. 7 that the pile in the control cylinder displayed more displacement than the pile in the test cylinder from the early loading increments and the difference increased as the load increased. The lateral capacities of the piles in the control and test cylinders were determined from the load–deflection curves, and found to be 0.12 and 0.19 kN, respectively.

The comparison between the lateral capacity of both piles showed that the lateral capacity of the pile in the test cylinder increased by almost 60%. The average undrained shear strength (at the locations of measurement) increased by 27% in this phase. These results confirmed that the soil shear strength in the vicinity of the pile in the test cylinder has significantly increased, more than the increase detected

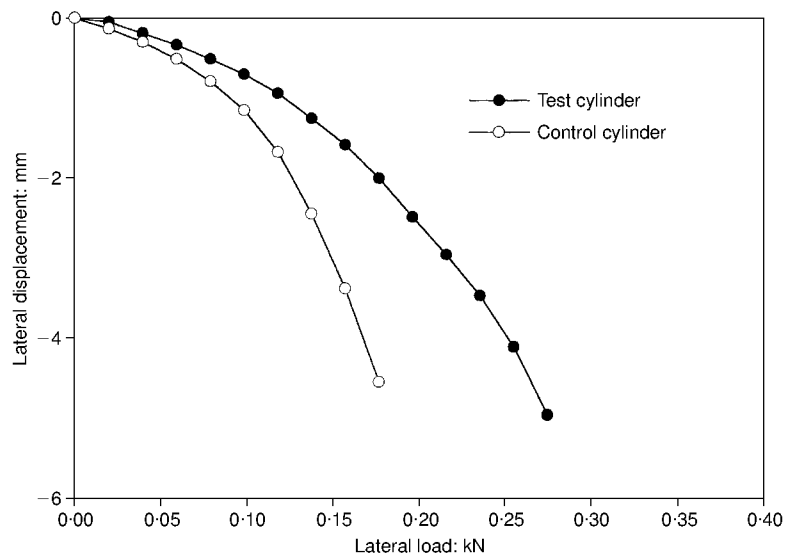


Fig. 7. Lateral load–displacement curve (second phase of treatment)

from the vane shear tests at the locations of measurement. It can also be noted that the ultimate lateral loads of the piles in both cylinders were less than the capacities achieved in the first phase. This was because the soil surrounding the piles was remoulded due to loading the piles till failure after the first phase of treatment and did not have enough time to regain strength. However, the pile in the test cylinder still had a 60% increase in capacity.

#### Treatment effect on cyclic response of piles

Two-way lateral cyclic response tests were performed on two identical piles in the control and test cylinders after the second phase of soil treatment. The same loading set-up and procedure discussed earlier were used.

The load–displacement relationship for the first and the 15th cycle is shown in Fig. 8. It can be seen from the figure that the pile in the treated cylinder showed a stiffer response in the first loading cycle, and that the difference in the stiffness increased after the 15th loading cycle. This was the same behaviour observed after the first phase of treatment. The degradation factors were found to be 0.51 and 0.44 for the piles in the test and control cylinders, respectively. The improvement in the cyclic response due to the treatment in this phase was about 14.6%. The high degradation of the soil that was noticed in this phase may be attributed to the previous failure of these piles when tested under axial loading after the first treatment phase.

#### High-voltage application (phase III)

A  $-10$  kV DC voltage was used for 33 days in the third treatment phase. The lateral static and cyclic load tests were performed on the piles after the treatment was completed successfully.

#### Treatment effect on lateral pile capacity

The load–displacement relationship obtained from the static load test is shown in Fig. 9. It can be seen that the pile in the control cylinder displayed more displacement than the pile in the treated cylinder from the early loading stages. The failure loads were found to be 0.08 and 0.09 kN for the piles in the control and test cylinders, respectively. The increase in the lateral capacity was almost 12% in this treatment phase.

The previous results clearly showed that the shear strength decreased significantly due to the failure in the first

two loading tests. However, the high-voltage treatment served to accelerate shear strength recovery.

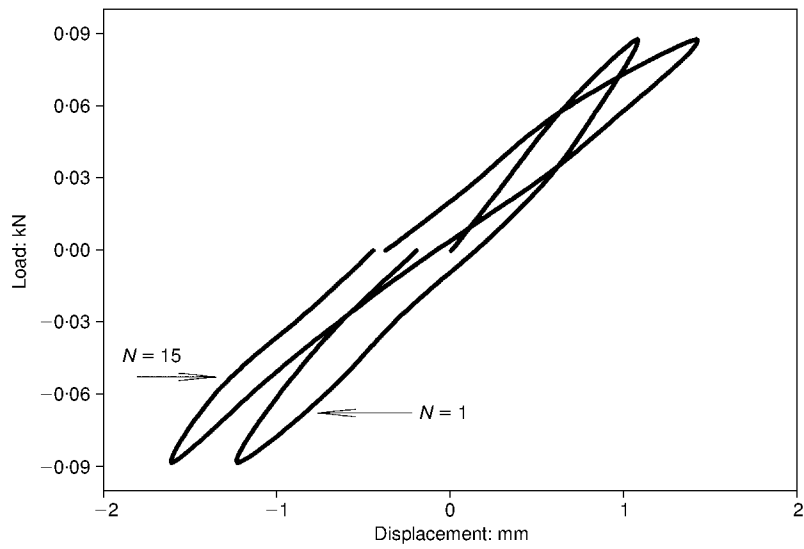
The lower increase in the pile capacity compared with the first two treatment phases may be attributed to the lower voltage applied ( $-10$  kV) or to the disturbance in the soil close to the pile (separation between the piles and the soil) due to the failure in the previous loading tests.

#### Treatment effect on cyclic response of piles

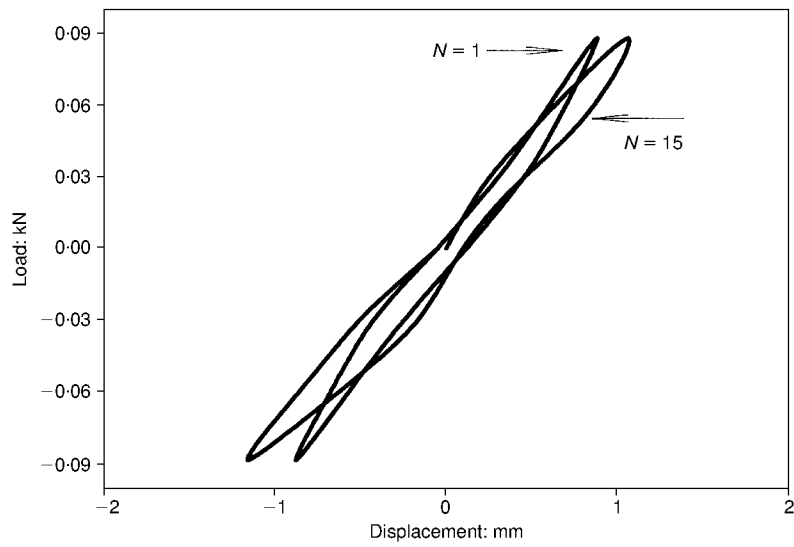
Lateral cyclic load tests were performed on two identical piles after the third phase of treatment. The load–displacement relationship for the first and the 15th cycles is shown in Fig. 10. Although the difference in the response of the two piles was much smaller in this case, the same trends were observed. The pile in the control cylinder experienced more displacement than the pile in the test cylinder after the first cycle, and the difference increased after the 15th cycle. The degradation factors evaluated after 15 cycles were found to be 0.506 and 0.496 for the piles in the test and control cylinders, respectively. The improvement in the cyclic response was only 2%. This negligible improvement may be attributed to the low voltage ( $-10$  kV) used in this phase of treatment. Also, the repeated loading may have affected the soil stiffness.

## Discussion

The applied voltage was normalized by the measured initial undrained shear strength to account for the initial soil condition at each treatment phase. Fig. 11 represents the relationship between the normalized voltage and the percentage increase in the lateral capacity of the piles. It can be seen from the figure that the first treatment phase (20 kV) resulted in the largest increase in the lateral capacity of the piles. The moderate increase in the lateral capacity of the piles after the third treatment phase may be attributed to three factors. First, the increase in soil shear strength around the piles was proportional to the applied voltage. Second, the treatment effect was inversely proportional to the initial undrained shear strength of the soil. Third, the failure in the previous loading test resulted in the development of a permanent gap between the pile and the soil, which diminished the effect of the treatment on the pile capacity. The influence of these factors requires further investigation.



(a)



(b)

Fig. 8. Load–displacement curve for  $N = 1$  and  $N = 15$ : (a) control cylinder; (b) test cylinder (second phase of treatment)

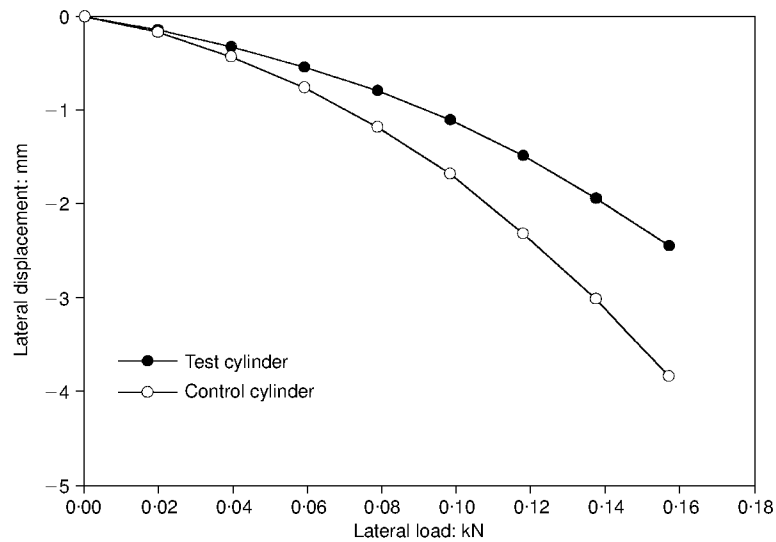
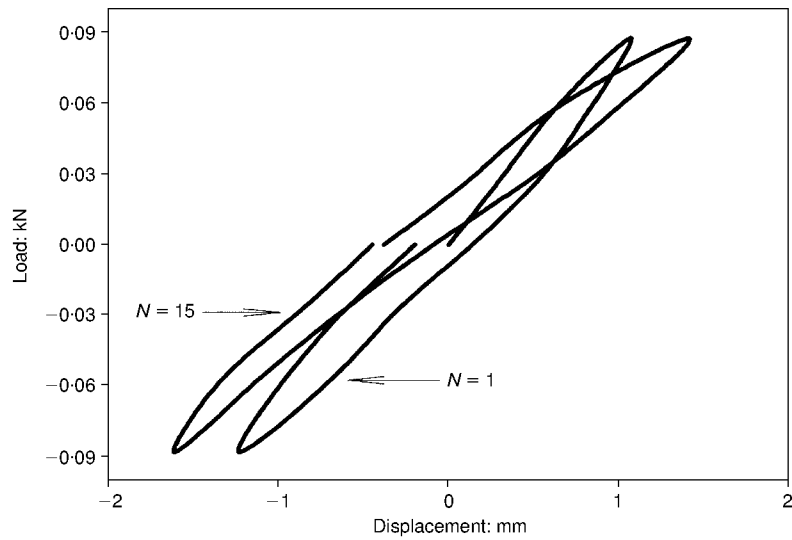
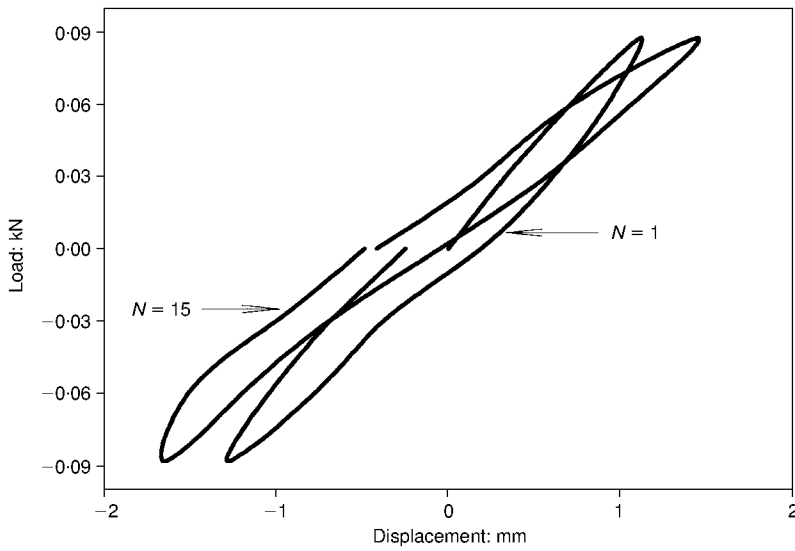


Fig. 9. Lateral load–displacement curve (third phase of treatment)





(a)



(b)

Fig. 10. Load–displacement curve for  $N = 1$  and  $N = 15$ : (a) control cylinder; (b) test cylinder

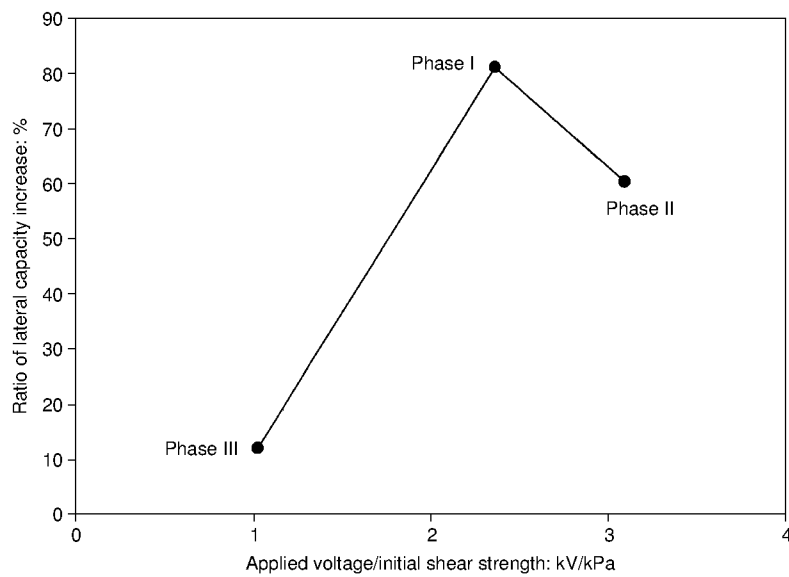


Fig. 11. Relationship between the ratio of lateral pile capacity increase and normalized voltage

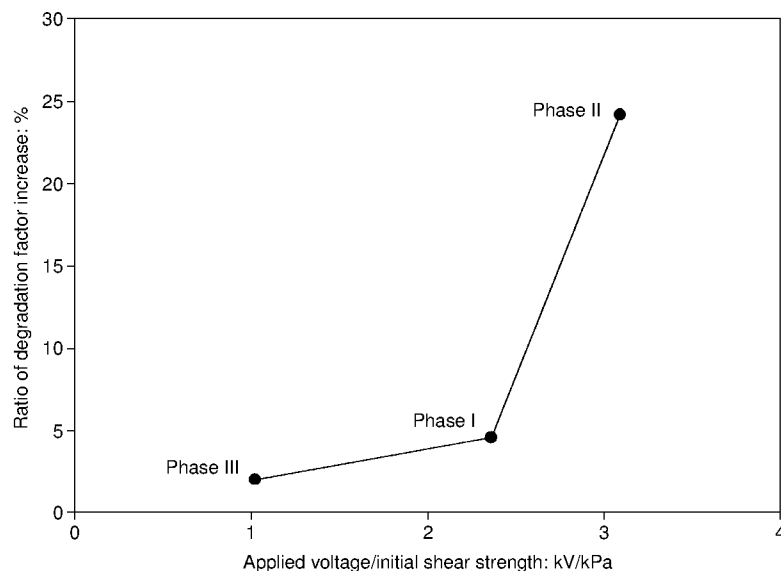


Fig. 12. Relationship between the ratio of increase in degradation factor and normalized voltage

The increase in the degradation factors is plotted versus the normalized voltage for each phase of treatment in Fig. 12. It can be seen from the figure that maximum improvement occurred in the second treatment phase (30 kV). However, the increase in degradation factors in the first and third treatment phases was almost the same.

The moderate decrease in the soil degradation factor after the third phase of treatment may be attributed to the soil remoulding as failure occurred in the first and second loading tests.

## Summary and conclusions

The effects of high-voltage electrokinetic treatment on soil and pile behaviour were investigated in an experimental laboratory set-up. Two identical steel cylinders 1.37 m in diameter and 1.52 m deep were used in the test programme. One cylinder was used to implement the treatment and the other was used as a control to compensate for the effect of natural ageing and drying of soil.

Eight model piles were installed in simulated marine clay, four in each cylinder. Five insulated electrodes were used to execute the treatment. Static lateral and cyclic load tests were carried out after applying negative high voltages of 20, 30 and 10 kV in three treatment phases.

The results were compared for both cylinders after each phase of treatment. It was observed that the lateral pile capacity increased by 81, 60 and 12% after the first, second and third treatment phases, respectively. The stiffnesses of the piles also increased due to treatment. Furthermore, the cyclic performance of the piles improved after treatment. This improvement was evaluated in terms of the increase in the soil degradation factors, which were found to be 4.6, 14.6 and 2% after applying 20, 30 and 10 kV, respectively.

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